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Temperature sensor based on a liquid crystal plasmonic wire grating

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***Abstract*— In this work, a novel liquid crystal (LC) temperature sensor, based on a Silver (Ag) wire grating, is proposed and theoretically analyzed. The structure is composed of several Ag nanowires distributed in a parallel configuration (see Fig. 1). These wires can be deposited onto a silica glass or plastic substrate. Another substrate positioned on it is separated by spacers of 1.2 µm. The resulting cavity is filled with an E7 LC. The high thermo-optic coefficient of the LC is used to modify the plasmonic resonance of the wire grating. The structure is simple and easily scalable. The application of a 420 nm laser allows an output power ratio sensitivity of $16.7 \cdot 10^{-2}$ dB/ºC with a high linearity. This is ten times more than other related temperature sensors based on light intensity variation.**

Keywords—Temperature sensing; plasmonic resonance; liquid crystal; nanowires.

I. Introduction

One of the most measured physical magnitude by the industry is the temperature. From an industrial point of view, the sensor measuring of this magnitude is required to be simple, small in size, low cost, and has the common characteristic of a sensor, to be reproducible and stable. Another important parameter in some environments is electromagnetic compatibility. There are many situations requiring sensors that do not emit any kind of electrical or electromagnetic signals. The classic temperature sensors working with electrical signals are unsuitable for the use in industrial processes where electromagnetic interferences are usually present or in medical environments where the field strengths caused by some equipment can be very high, producing errors in metallic sensors. To solve this problem, the most common approach is the use of optical fiber sensors [1, 2]. Fiber optic sensors have some unique advantages over conventional sensors. They can provide very precise measurements and usually have a very rapid response. Most of fiber-optic techniques for temperature sensing are based on phase (coherent) or amplitude variations of a beam intensity (incoherent). Phase-based designs using interferometric configurations such as a Mach–Zehnder [3] Bragg gratins [4] or a Fabry–Perot (F–P) type [5] have been proposed. These devices are highly sensitive. However, they require conditioning circuitry or special equipment to measure the output signal (usually lambda shifts). On the other hand, amplitude-based devices use several physical phenomena such as light attenuation [6] or fluorescence [7]. Some of the most recent works on intensity sensors included a macrobend [8], fluorescence and glue [9], or a plastic optical fiber (POF) macrobend [10]. All of them have sensitivities around $1.5 \cdot 10^{-2}$ dB/°C. In these studies, the temperature ranges are 20–73 °C in POF fibers and 0–100 °C in silica fibers. Another option to measure the temperature is the use of LC materials. LC temperature sensors are usually based on the refractive index dependence with temperature of the LC. The most relevant works are based on phase variations of the light. The output signal is lambda shifts. For example, a Fabry-Perot cavity filled with a nematic LC has been used by several authors. It is worth mentioning the work of Hak-Rin Kim et al., that obtain lambda shifts of 1.05 nm/ºC for maximum temperatures of 65 ºC [11]. Others works have used another type of structures as photonic crystal fibers [12]. For instance, Y. Wang et al., with a sensitivity of 54.3 nm/ºC but for very small temperature ranges (34 ºC to 35.5 ºC) [13]. D. J. Hu et al. with sensitivities of -3.9 nm/ºC ranging from 44 ºC to 53 ºC [14]. In summary, these sensors are complex to build, or take measurements (low sensitivities, a spectrum analyzer is frequently required, etc.). In this study, we will focus on a novel technology that has arisen in the last years, the plasmonic resonances of particles at nanometric size.

Active Plasmonics is mainly focused on the control of plasmonic phenomena of metallic nanostructures through the use of active media [15] [16] [17]. LC is one of the most widespread media due to their important optical anisotropy. In addition, there are several ways to modify their refractive index of LC. Light-driven, electric-driven and also, thermal-driven methods are described in the literature [18]. Moreover, the optical properties of LC are very sensitive to the surrounding conditions, in particular the ambient temperature. Any temperature gradient produces a noticeable variation of the optical properties of the LC, simultaneously inducing modification of the plasmonic phenomena.

In this work, this fact is exploited by using a plasmonic wire grating structure. The response improves the characteristics of previous LC sensors and even some commercial sensors (e.g. 16 dB/ºC, ten times more than other reported intensity based temperature sensors).

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II. Structure

The structure is composed of one array of nanowires placed onto a glass or plastic, it could be deposited also into a fiber optic core. The structure and dimensions of the LC device are determinant in order to have a high enough sensitivity.. Several materials can be employed, Silver (Ag) or Gold (Au) are the most common ones. In this case, Ag is studied. Although the thickness is not a critical parameter, the lower the thickness, the highest the response time. The LC molecules have an elongated shape that causes different molecular polarizabilities between the long and short axis. The effective refractive index depends on the angle of long axis of the molecules. There is needed an alignment layer to avoid different orientations of the LC molecules. For this reason, a homogenous alignment layer, with the same direction as the polarized light is necessary to exploit the extraordinary dependence of the LC with temperature. The molecules arrange parallel to the layer when the cell is filled. This sensor can be fabricated in a plastic or glass cell, as well as embedded in a fiber optic cavity.

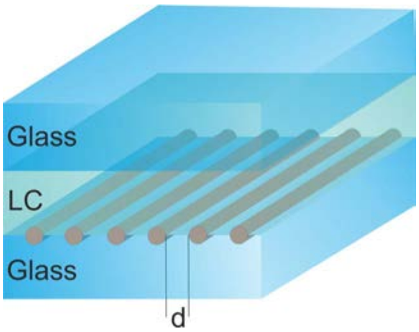

Fig. 2. Structure. Note drawings are not to scale.

III. Results

The structure depends on the polarization and angle of the incident wave. For this reason both a TE and TM cases are studied and normal incidence is considered. By using Finite Element Method (FEM) the response of the sensor can be estimated. The results show the Euclidean normalized electric field for three different wavelengths at 15ºC. Also the transmission coefficient (S21) for the visible spectrum of the transmitted light, between 400 nm and 600 nm is studied. There is a plasmonic resonance at the wavelength of 420 nm when the sensor is at 55ºC. This effect is used to exploit the change of the plasmonic resonance with temperature by applying a 420 nm laser. The result is an intensity variation as a function of temperature. The output power ratio in decibels shown a high linear sensitivity.

A. *Sensor response spectrum*

When the wavelength is short enough in comparison to the distance between nanowires, and the light is applied at certain angle, one or several diffraction orders are formed. For this reason, normal incidence is considered. The result is very different as a function of the LC compound used. The application of the sensor will determine the type of compound. Three different wavelengths are displayed in Fig. 2. Here it can be observed how the plasmonic resonance is changes by the different wavelengths.

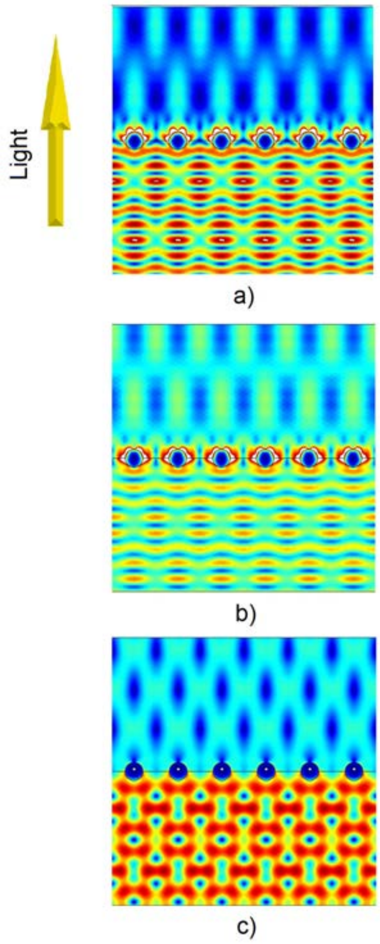

Fig. 1. Normalized electrical field inside the structure at 15 C for a) 422 nm, b) 441 nm and c) 600 nm.

The collective oscillation of electrons in the Ag nanowire is stimulated by the incident light. In this case (15ºC) a resonance condition is established at 441 nm because the frequency of light photons matches the natural frequency of surface electrons that are oscillating against the restoring force of the positive nuclei. This resonance can be controlled by means of the surrounding medium. As can be seen in Fig. 3 the peak resonance is established at different wavelengths. In this figure four different temperatures in the range from 15ºC to 55ºC, for a TE polarization, is shown.

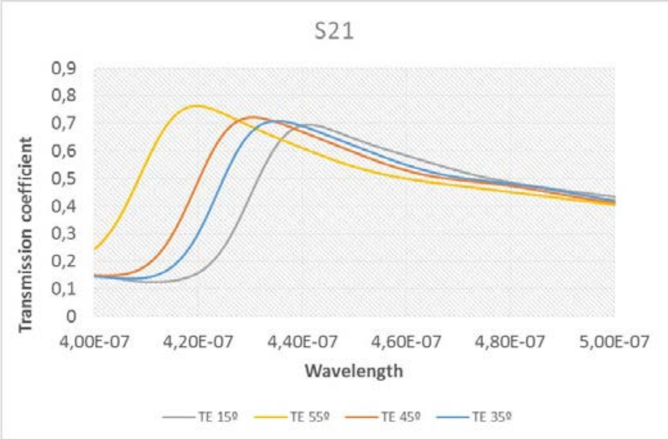

Fig. 3. Spectral response of the transmission coefficient S21.

This is caused by two physical effect, the first one is that the plasmonic resonances of a determined nanoparticle depend on the refractive index of the surrounding medium. The second one is the variation of the refractive index with temperature that occurs in the nematic LC. As can be seen a sensitivity of 4 nm/ºC is obtained. In comparison with other proposed sensors based on lambda shifts the sensitivity is high in a broad range of temperatures. Despite this, some problems as the difficulty to measure with a spectrum analyzer are still present. For this reason we propose an amplitude method to improve the sensor characteristics.

B. Sensor response by using one lambda

In order to exploit the high reject band produced at the resonance wavelength of the maximum temperature, a laser source with the same wavelength is applied as light source. The result is an intensity variation of the source caused by the translation of the resonance wavelength of the NP as the temperature decreases. In this case a 420 nm laser is used. The response curve of the sensor has a maximum sensitivity of $16 \cdot 10^{-2}$ dB/ºC for a temperature range of 15 to 55ºC. This is ten times more than other related intensity sensors. Moreover the sensitivity is high linear with a regression coefficient of 99.4%. In spite of this, these results can be modified by using another type of LC. The use of different compound as well as an optimization study of the proposed structure has to be further investigated.

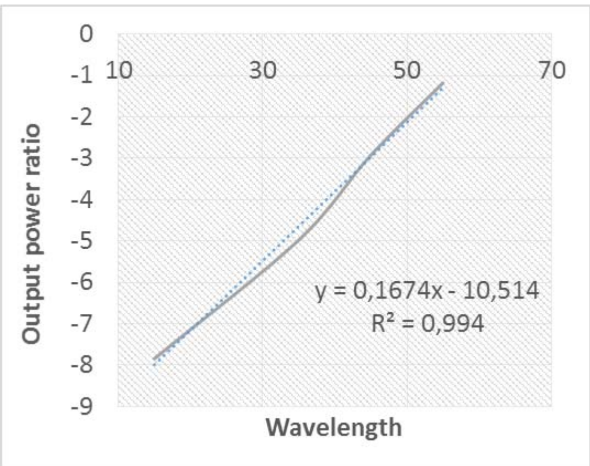

Fig. 4. Output power ratio for a 420 nm laser.

IV. Conclusions

A novel idea in the research field of temperature sensors has been presented. The sensor response has been theoretically analyzed by FEM. The proposed structure can be applied to glass or plastic substrates and even could be integrated in an in-line fiber optic cavity. The structure is simple and has an active area easy to scale. This new LC temperature sensor has several advantages with respect to other temperature sensors. Can be used as phase and amplitude temperature sensor. In the latter case, a very linear response with a high sensitivity has been observed. An optimization of the structure is expected to bring higher sensitivities. Moreover the use of other LC compounds can change the temperature range as well as the sensitivity. These ideas have to be further investigated.

This sensor can be used in LCD displays, LCD projectors, portable equipment or any application where its properties procure an advantage with respect to current available sensors. This work has presented and characterized a novel idea, and opened new avenues for research in the field of temperature sensing.

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